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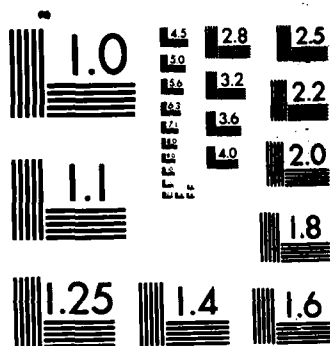
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EVALUATION OF CHARGED FOG FOR SMOKE CLEARING IN SHIPBOARD FIRES

John S. Kinsey and
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Accidental fires occurring on-board Navy surface vessels create massive quantities of dense black smoke. To increase visibility and improve firefighting capabilities, appropriate technology is needed for clearing smoke from corridors and passageways.

In response to this need, Midwest Research Institute has conducted research to evaluate the use of charged water droplets (fog) for clearing smoke from a 4.5-m^3 test chamber under controlled laboratory conditions. As part of this effort, a new type of charged droplet generator (electrostatic fogger) has been developed which is both novel in its approach and unique in design.

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The results of the study indicate that smoke can be visually cleared from the test chamber within 15-60 sec after application of the charged fog, with similar trends observed for particle number concentration. Also, the electrostatic fogger developed in the study is superior in many respects to other devices of a similar capacity and, therefore, represents an advancement in charged fog technology. *Keywords:*

to FLD's

PREFACE

This report was prepared by Midwest Research Institute for the U.S. Naval Research Laboratory under Contract No. N00014-84-C-2189. Dr. Joseph Leonard acted as the Contracting Officer's Technical Representative for the project. The work was performed in Midwest Research Institute's Air Quality Assessment Section (Dr. Chatten Cowherd, Head). The report was prepared by Mr. John Kinsey (Principal Investigator), and Mr. Frank Pendleton.

Approved for:

MIDWEST RESEARCH INSTITUTE

M. P. Schrag, Director
Environmental Systems Department

12 July 1985

CONTENTS

1. INTRODUCTION

Accidental fires occurring below decks of Navy surface vessels create massive quantities of dense, black smoke. This smoke soon fills the corridors and passageways of the vessel restricting the visibility of both the crew trying to escape and firefighters attempting to locate and extinguish the fire. Because good visibility is imperative to effective firefighting, appropriate technology is needed to clear the smoke created in shipboard fires.

In response to the above need, Midwest Research Institute (MRI) has conducted research under the sponsorship of the U.S. Naval Research Laboratory (NRL) to evaluate the use of charged water droplets (fog) for smoke clearing under controlled laboratory conditions. Experimental data collected during the program indicate that charged fog can effectively clear smoke in a 4.5-m^3 test chamber within 15 to 60 sec after commencing application. Also, as part of the above effort, a novel charged droplet generator (electrostatic fogger) was developed which exhibits operational characteristics which are superior to other devices of a similar capacity.

The following sections summarize the results of the above research program. Section 2 provides a technical background on charged fog technology; Section 3 describes the charged droplet generator developed during the program. In Section 4, the experimental apparatus, procedures, and results derived from the research are presented. Finally, in Section 5, the conclusions reached from the results obtained during the study are outlined as well as recommendations for further development.

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2. TECHNICAL BACKGROUND

2.1 AEROSOL FORMATION IN SHIPBOARD FIRES

Smoke from the uncontrolled burning of a hydrocarbon fuel (or other com-
bustible material) is created by a combination of thermal degradation (py-
rolysis) and incomplete combustion which produces an aerosol of carbonaceous
particulate or soot.[1] In ventilation limited flames, such as those found in
shipboard fires, partially oxidized gases and condensed phase products are
formed creating dense black smoke and soot.

There is a large body of information contained in the literature which at-
tempts to define soot formation in smoking flames.[1-3] In general, these
studies describe the creation of soot as consisting of three basic stages.
These stages are: (a) particle inception; (b) particle growth by hetero-
geneous surface reactions; and (c) particle coagulation.

Particle inception consists of the creation of very small, spherical par-
ticulate (< 20 $\overset{\circ}{A}$ in diameter) which are formed by condensation reactions
involving certain gas phase species. The mass of these primary particles
are then increased through incorporation of various gaseous compounds onto
the surface of the particle by which the bulk of the solid phase material
is generated. Surface growth reactions lead to an increase in the total
mass of soot formed with the number of individual particles remaining es-
sentially unchanged. These larger particles (200 to 300 $\overset{\circ}{A}$ in diameter)
then coagulate to form chain-like agglomerates or clusters.

As soot particles are formed in the ionizing environment of the flame zone,
they usually acquire an electrostatic charge.[3] The exact mechanism(s) by
which these ions are formed is not yet fully understood. It has been found,
however, that soot particles are usually positively charged with the concen-
tration of charged particles increasing with increasing fuel equivalence
ratio (such as would be found in shipboard fires).[3,4] Figure 1 illustrates
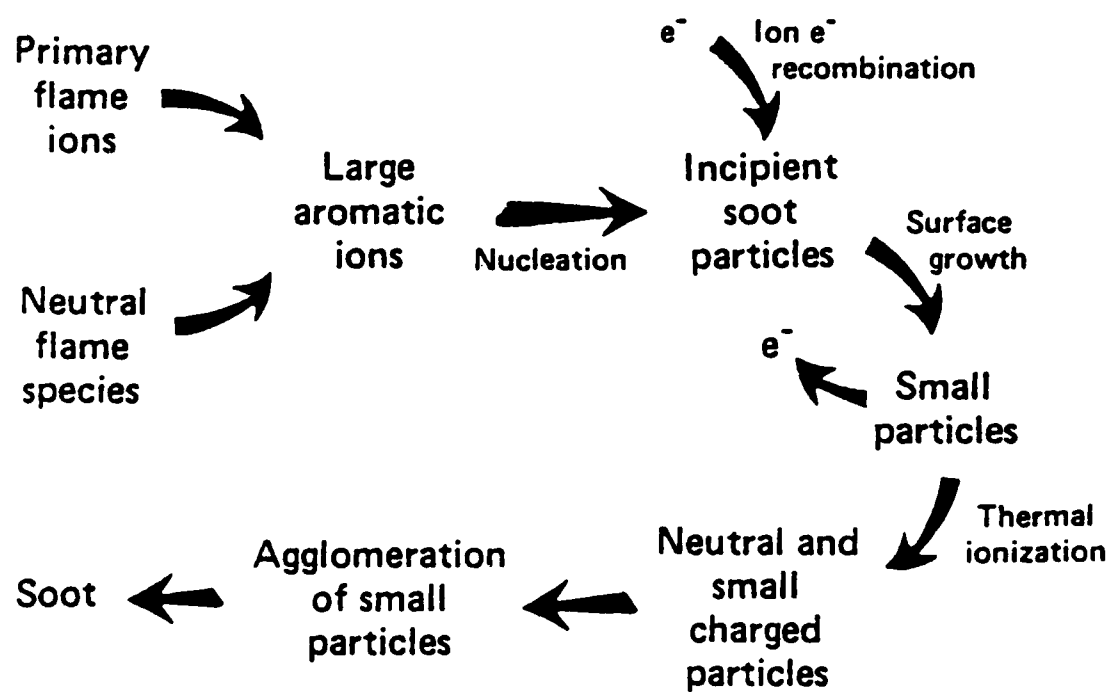one proposed model of soot formation in smokey flames.[1]

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Figure 1. Proposed soot formation model.[1]

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2.2 CHARGED FOG FOR SMOKE CLEARING

As discussed in Section 2.1 above, there is substantial technical evidence
which indicates that most aerosols acquire a slight electrostatic charge
during generation.[3,7] By the injection of oppositely charged water droplets
(fog) into the same flow regime, a significant enhancement in the capture
and removal of the smaller particles (1-2 μm) can be achieved over that
obtained either by uncharged water droplets or by natural processes. The
following sections describe both the theory of operation and existing tech-
nology for the generation of charged fog.

2.2.1 Theory of Operation

The removal of fine particles from an aerosol cloud dispersed throughout a
wide area is difficult due to the particles' low inherent mobility, unfavor-
able inertial properties, and uncontrollable external factors. Prior re-
search has shown that a significant enhancement in fine particle collection
and removal can be achieved by electrostatic attraction through the use of
oppositely charged water drops.[7-10]

There are various physical mechanisms which must be considered when analyz-
ing the interaction between two dissimilar aerosols. A number of investi-
gators have studied such relationships in some detail. The collection effi-
ciency (E) of suspended particles by water droplets can be expressed in the
general form:[9-11]

$$E = 1 - \exp\left(-\frac{3}{2} \cdot \frac{Q_1}{Q_g} \cdot \frac{t}{D_d} \, \bar{\eta}\right) \tag{1}$$

where: E = overall collection efficiency

Q_1 = liquid volumetric flow rate

Q_g = gas volumetric flow rate

t = contact time

D_d = Sauter mean droplet diameter

$\bar{\eta}$ = average single droplet capture efficiency

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From equation (1) it can be seen that the average single droplet efficiency ($\bar{\eta}$) is the prime factor in determining the collection of fine particles by water droplets, thereby removing them from suspension by a combination of agglomeration and gravitational settling. The value of $\bar{\eta}$ can be obtained by solving the various equations of motion taking into consideration the individual forces acting on the particles. The remainder of the terms in the equation relate to the operating characteristics of the droplet generator.

The interaction between water droplets and aerosol particles, and the collection efficiency of a single droplet falling under its terminal velocity have been topics of many detailed investigations. Greenfield was probably the first to demonstrate that in the absence of an electric charge on either the droplets or the aerosol particles, the collection efficiency of water droplets has a minimum for particles with radii near 1 μm.[10,12] This minimum (or gap) results from the fact that Brownian diffusion dominates particle scavenging for very small particles while inertial impaction is most predominant for particles larger than 2 or 3 μm in diameter. For particles in other size ranges, neither of these two processes is very effective. However, both the phoretic (gradient in temperature or vapor pressure) and electric forces play a significant role in the collection of suspended particulate in this region of the size spectrum.

In a series of papers, Pruppacher, Grover, Beard, and Wang at the University of California at Los Angeles (UCLA) have solved the equations of motion for charged and uncharged free-falling raindrops to obtain the single droplet collection efficiency for the system.[13-15] Some of the results of the UCLA model are shown in Figures 2 through 4.

To illustrate the so-called "Greenfield Gap," Figure 2 presents the theoretical collection efficiency of single water droplets for aerosol particles of various radii at 75% relative humidity, a pressure of 900 mb, and a temperature of 10°C. As shown by Figure 2, the collection efficiency goes to minimum values for particle radii between approximately 0.8 to 2 μm in all cases.

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Figure 2. Calculated single droplet collection efficiency as a function of particle radius in air at 10°C, 900 mb, and a relative humidity of 75% for a droplet radius of (A) 42 μm, (B) 72 μm, (D) 173 μm, and (E) 310 μm.[10]

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Figure 3. Calculated single droplet collection efficiency in air of 10°C and 900 mb for a 72 μm radius droplet with a relative humidity of: (A) 50%, (B) 75%, (C) 95%, and (D) 100%.[10]

Single Droplet Collection Efficiency

Particle Radius (μm)

10^0

10^{-1}
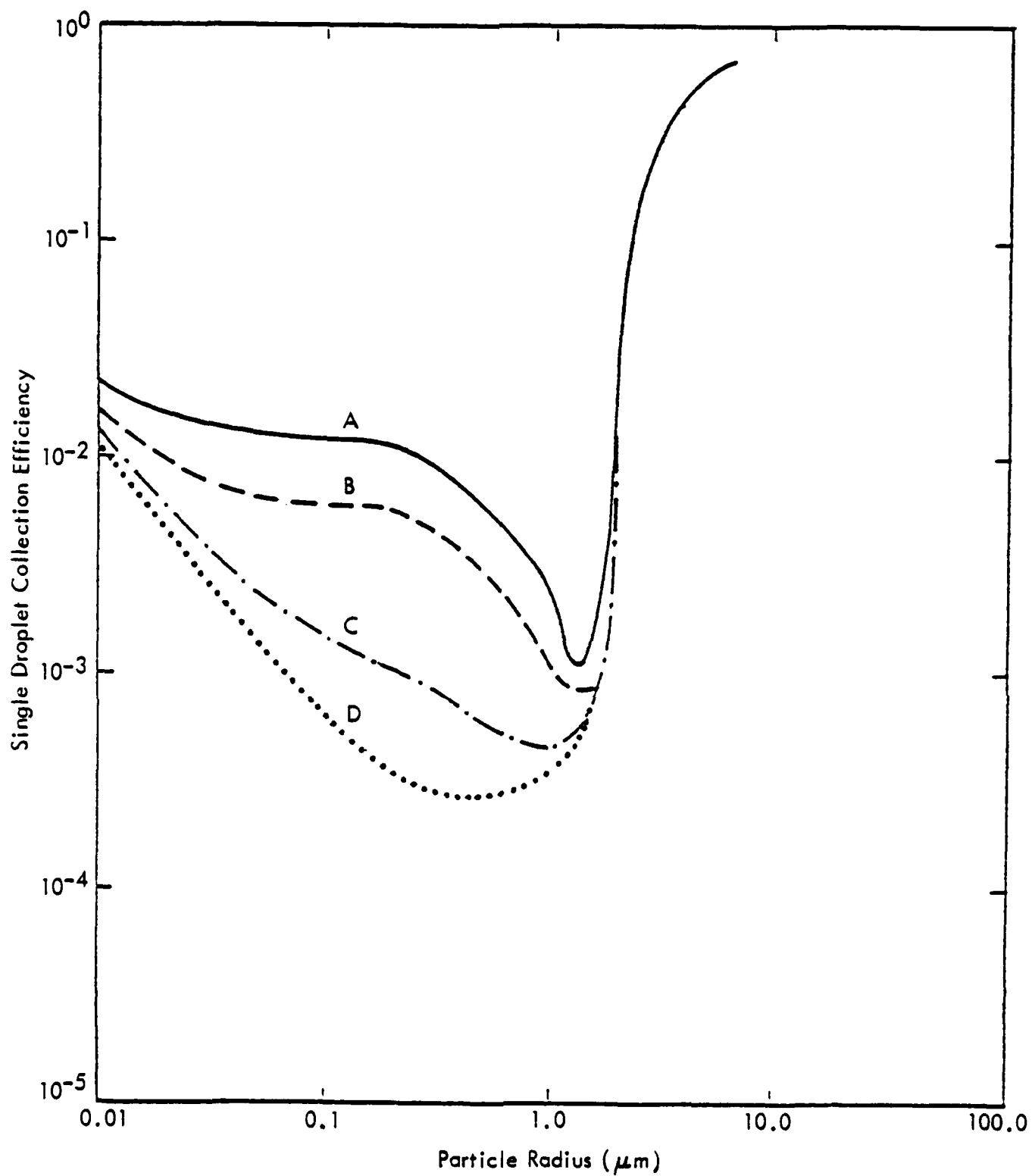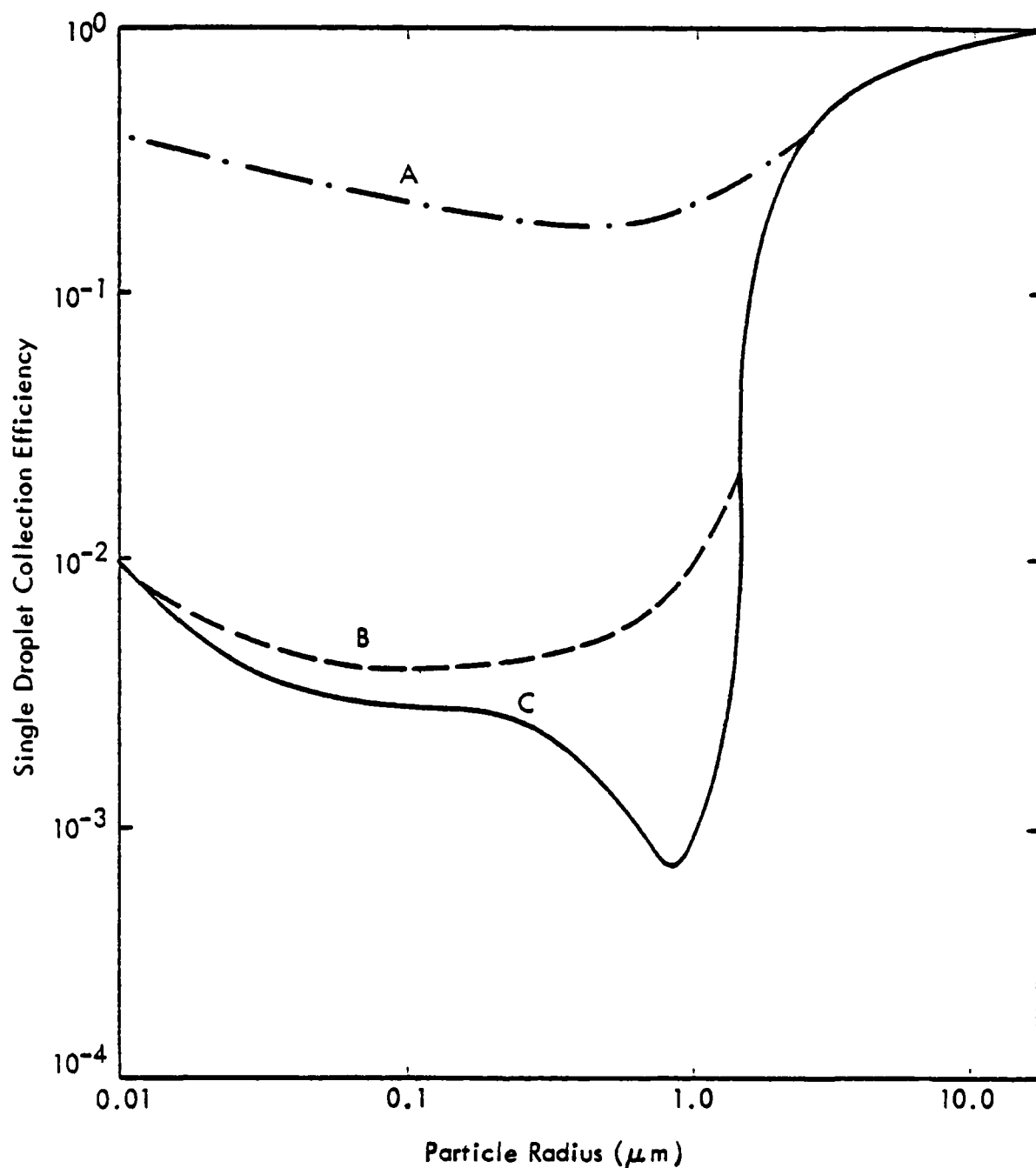
10^{-2}

10^{-3}

10^{-4}

0.01 0.1 1.0 10.0

A

B

C

Figure 4. Calculated single droplet collection efficiency in air of 10°C and 900 mb for a 106 μm radius droplet at 75% relative humidity for droplet and particle charges of (A) ±20 esu cm^2, (B) ±1 esu cm^2, and (C) zero charge.[10]

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For the case of phoretic forces acting on the particle, Figure 3 shows the calculated collection efficiency versus aerosol particle radius for a water droplet of 72-μm radius, with relative humidity (RH) as the major variable.[15] As shown, when the RH changes from 100 to 50%, the phoretic forces alone could raise η by an order of magnitude or more. As the figure also shows for larger particles (2 to 3 μm and larger in radius), the collection efficiency is essentially independent of RH. It should be noted, however, that the evaporation rate increases as RH decreases which, in turn, reduces the lifetime of the droplet in the medium. Consequently, rapid evaporation at low RH tends to reduce the overall ability of a water droplet to remove fine particles from suspension.

So far, the effect of charging the droplets or the aerosol particles have not been considered. Figure 4 shows three curves for the single droplet collection efficiency versus particle radius for charged and uncharged droplets with a radius of 106 μm at 75% RH.[15] From Figure 4, it can be seen that the introduction of electrostatic charges on the droplets and the aerosol particles (i.e., smoke) practically eliminate the Greenfield Gap and, depending upon the amount of charge, the collection efficiency of submicron particles is enhanced by more than an order of magnitude. This effect is the fundamental principle on which charged fog technology is based.

From the above discussion, it can be concluded that when the aerosol particles are small, or when the relative velocity between the particle and the droplet is very small, the particle can be considered to have negligible inertia, and the electrostatic force becomes the dominant mechanism for collection of particles in this size range. The single droplet collection efficiency of a charged particle by an oppositely charged droplet is given by the relation:[10]

$$\eta = 4K_c = \frac{-4\ C\ Q_c\ Q_p}{24\ \pi^2\ \varepsilon r\ R^2\ \rho\ U_o} \tag{2}$$

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where: η = single droplet collection efficiency

K_c = electrostatic parameter

C = Cunningham slip correction factor

Q_c = droplet charge

Q_p = particle charge

ε = dielectric constant

r = particle radius

R = droplet radius

ρ = viscosity

U_0 = free-stream velocity

The above relation shows that, for a given particle size, the electrostatic forces are directly proportional to the magnitude of the charges on the droplet and particle and inversely proportional to the square of the droplet radius and its free-stream velocity. Physically, this would indicate that when the droplet free-stream speed is slower, the particle spends a greater amount of time in the vicinity of a droplet. Thus, the electrostatic forces between the droplet and particle are effective for a longer period of time, enhancing particle collection. The single droplet collection efficiency given by equation (2) may be integrated over all droplet and particle sizes and substituted in equation (1) to obtain the total particle control efficiency of an electrostatically charged water spray system.[9]

2.2.2 Existing Charged Fog Technology

The generation of electrically charged droplets has been studied for a number of years by investigators both in the United States and abroad. The uses of charged droplets have varied from the spraying of paint and other coatings to the application of pesticides and in gas cleaning equipment.[16-18] Recently, charged fog has been investigated for the removal of suspended particles generated by industrial processes in response to environmental

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concerns.[7,8,10] Included in this work was research conducted by the principal author for the U.S. Environmental Protection Agency.[9] The following describes currently available charged fog technology.

A number of different techniques have been developed to generate charged droplets. Each of these techniques use either of three mechanisms for imparting an electrostatic charge to the droplets. These mechanisms include: ionized field (or ion attachment) charging; induction charging; and contact charging.

In ionized field charging, a corona is used to create a flow of ions which attach to the droplets as they pass through the region near the electrode. Induction charging involves the production of a uniform electric field around the spray to transfer or induce a charge on the droplets. Finally, contact charging involves connecting the atomizer directly to a source of high D.C. potential which charges the droplets at the instant of formation.

One of the principal investigators involved in the use of charged fog for the removal of suspended particles is Dr. Stuart Hoenig at the University of Arizona. Under a research grant from the U.S. Environmental Protection Agency (EPA), an electrostatic fogger was developed specifically for this purpose.[7] The manufacturing rights to Dr. Hoenig's original fogger was assigned to the Ransburg Corporation and later transferred to the Ritten Corporation of Ardmore, Pennsylvania. (A Ransburg fogger was used in the NRL study described in Section 2.3 below.) The Ritten Corporation produced four different sizes of charged fog generator (Fogger I, II, III, and IV), all based on the same basic design concept. This company recently went out of business, with the technology now residing with the Sonic Development Corporation of Mahway, New Jersey. One additional company, the Keystone Dynamics Corporation, also produces the smallest version of the Hoenig device (Fogger I).

The fogger developed by Hoenig for the EPA uses an off-the-shelf spray nozzle to generate and disseminate the water droplets. In some of the larger
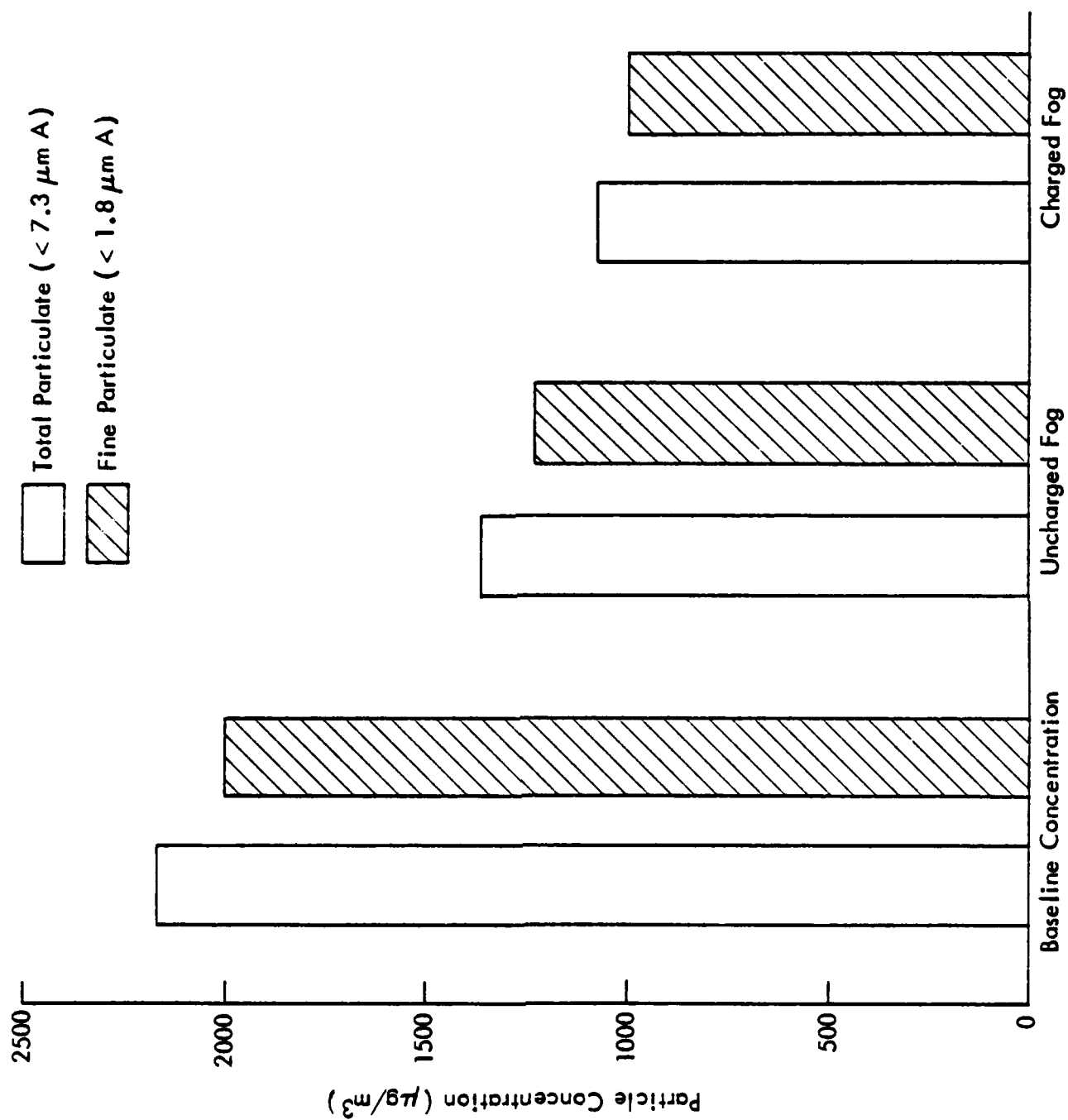
11

units a blower is also provided to help project the spray over greater distances. The droplets are charged by induction utilizing a metal ring surrounding the nozzle which is connected to a source of high potential.

There are a number of problems inherent in Hoenig's original design which tend to limit its usefulness in many applications. The first of these problems is that the commercial foggers use either a pressure-type or two-fluid spray nozzle to atomize the water. These types of nozzles have a tendency to clog if the water supply contains a high concentration of suspended solids.

The second, and more serious shortcoming of the Hoenig design, involves the type of charging mechanism being used. These units use induction charging which tends to apply a significant charge only to those droplets on the outside of the spray cone during heavy sprays with the remaining droplets having relatively little charge. Since the electrostatic attraction of particle to water droplet is critical to efficient capture and agglomeration, this is a significant problem.

To develop an improved fogger design, in 1979 a contract was issued by the EPA to AeroVironment, Inc. (AV). Instead of a traditional spray nozzle, this fogger (Charged Fog Generator or CFG) incorporates a rotary atomizer which needs neither high pressure air or water to generate the fog and is insensitive to solids found in the water supply. In addition, the CFG uses contact, not induction, charging of the water prior to atomization to assure that most, if not all, of the droplets acquire an adequate electrostatic charge. Tests have shown a significant increase (~ factor of 10) in the charge-to-mass ratio of the droplets generated by the CFG as compared with induction charging for devices of a similar capacity.[10,19]

To illustrate the effectiveness of the CFG to reduce the concentration of fine particles, Figure 5 shows the results of tests conducted during the processing of bentonite. The data in Figure 5 would indicate that an approximate 50% reduction in concentration was achieved with application of charged fog.

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Figure 5. Comparative reductions in fine particle concentrations with charged and uncharged fog.[10]

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At present only two prototypes of the AV fogger actually exist which would not be suitable for smoke clearing purposes. The prototypes are converted oil burners which are extremely heavy, bulky, and difficult to transport. The CFG is, however, an improvement over most commercially available foggers in many respects. It should also be noted that John Kinsey, the Principal Investigator of the program being discussed here, was also the Principal Investigator of the AeroVironment R&D efforts from its inception until July of 1980.

2.3 PREVIOUS WORK IN SMOKE CLEARING

NRL has conducted prior research in smoke clearing using both water sprays to which a surfactant has been added as well as a commercial electrostatic fogger.[5,6] With regard to the use of surfactants, some 90 different chemicals were evaluated as to their ability to wet smoke particles and to clear smoke from an experimental chamber.[5] It was found in this study, that the surfactants which more easily wet the particles also were the most effective in clearing the smoke in the test chamber. The major disadvantage to the use of surfactants would be the additional cost and logistics necessary to supply such material in bulk. In addition, some type of blending system (i.e., tank and metering system) would be required to disseminate a surfactant material in the event of a fire.

In a second study, NRL evaluated the use of a Ransburg electrostatic fogger (based on the original Hoenig patent discussed above but no longer being produced commercially) to clear smoke in a Quonset-type building containing a 3.05- x 4.27- x 3.05-m smoke chamber.[6] Approximately 1 L of No. 2 fuel oil was combusted to fill the chamber with smoke after which the Ransburg device was activated. Floodlights installed in the chamber were observed to determine the length of time required for the lights to become visible. Results of these experiments indicate that about 30 min were required to clear the smoke in the chamber without the fogger, with 12 and 3 min being required for uncharged and charged fog, respectively.[6]

3. ELECTROSTATIC FOGGER

One important accomplishment achieved during the program was the design, fabrication, and assembly of a new type of charged droplet generator. The design concept used in the construction of this fogger was both novel in its approach and unique to MRI. Basically, the electrostatic fogger utilizes a rotary atomizer and contact charging for the generation of highly charged water droplets, as described below.

3.1 MECHANICAL DESIGN

The electrostatic fogger developed by MRI during the program consists of a circular unit approximately 38 cm (15 in.) long and 20 cm (8 in.) in diameter. The body of the fogger is fabricated out of solid Plexiglas® which houses the various mechanical components making up the atomizer. The Plexiglas® body also forms the air cone portion of the atomizer whereby a high velocity jet of air is provided at the annulus of the rotating cup.

The internal components which comprise the atomizer are assembled on a single hollow shaft. Two precision sealed ball bearings pressed into appropriate stainless steel housings support the shaft on which is mounted both an impeller wheel and a brass atomizing cup. Water is provided to the cup through the center of the shaft with a rotary water seal installed at the opposite end. The entire assembly is electrically isolated from ground and operated at high potential supplied from an external D.C. power supply. Appropriate internal electrical connections are provided to assure contact between the voltage source and the water flow to the cup. A diagram of the electrostatic fogger is shown in Figure 6.

During operation, compressed air (~ 165 psig) is introduced tangentially striking the impeller which spins the hollow shaft at high speed (~ 25,000 rpm). The shaft in turn rotates the atomizing cup. The spent air from the impeller flows through openings in the forward bearing housing, past the spinning cup, and through the annular opening at high velocity. This high velocity annular jet helps break up the water into fine droplets as well as
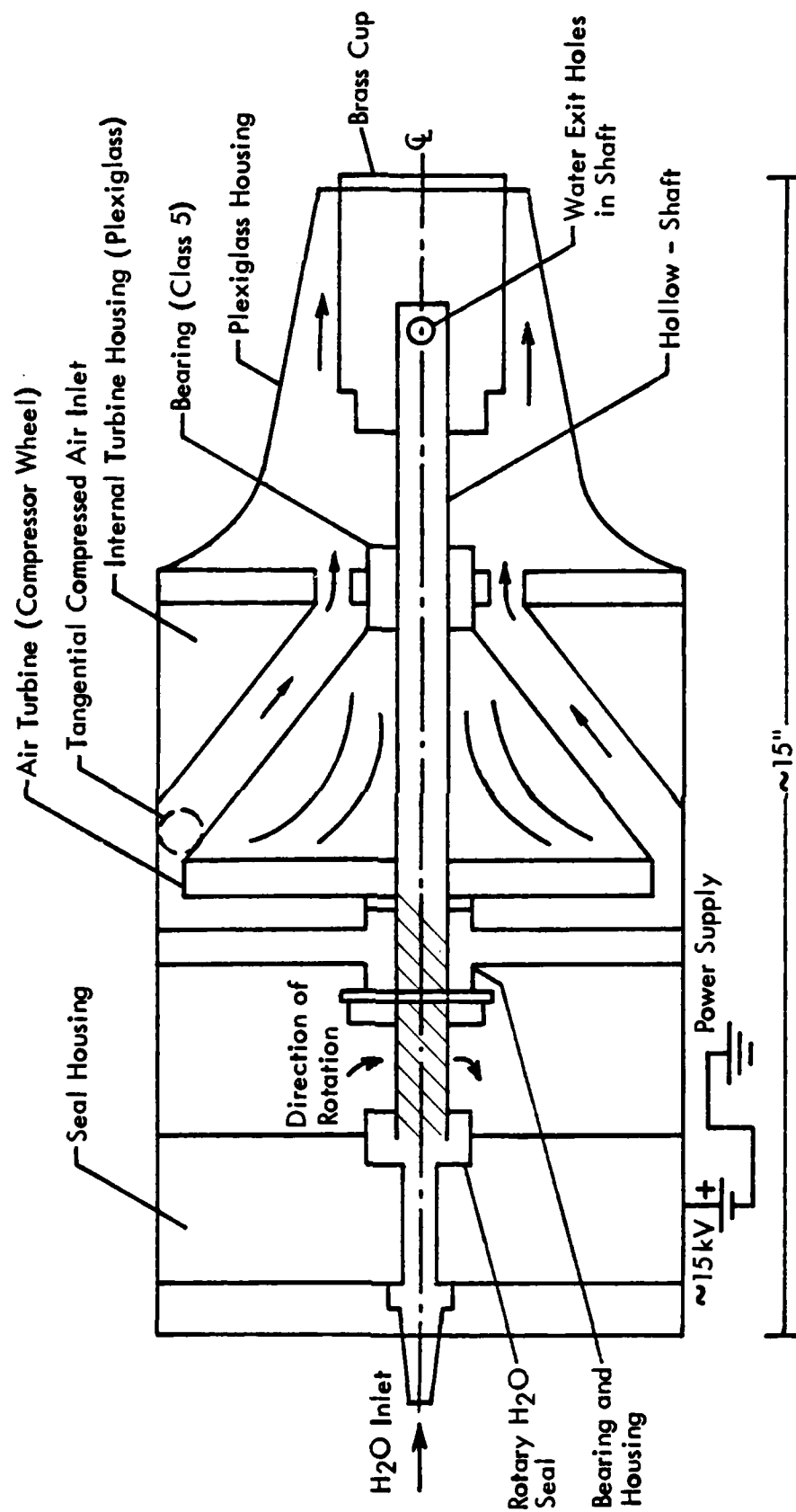
15

Figure 6. Diagram of electrostatic fogger.

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assists in projecting the spray forward. Water is introduced into the system through the rotary seal which acts as the interface between stationary and rotating components. The droplets are charged in the system by applying a high D.C. potential to the entire internal assembly. Current leakage to ground through the water line is eliminated by electrically isolating the entire water supply.

The only significant engineering problem experienced with construction and subsequent operation of the fogger involved the rotary water seal installed at the rear of the unit. It was found that the original seal had a relatively high coefficient of friction which caused the unit to either run poorly or to overheat and stop when the fogger was operated for extended periods. A contributing factor was the fact that the impeller used in the fogger was originally designed as a compressor wheel. Thus, although the pitch of the blades were conducive to producing high rotational speeds, they were generally inappropriate for turning the shaft against any significant resistance.

To solve the above problem, a special rotary seal which uses low friction-producing materials was located and purchased. Upon installation of the improved seal, there was no longer any major difficulty with operation of the fogger.

3.2 DROPLET SPECTRUM

The size distribution of the droplets generated by the fogger were determined using magnesium oxide coated slides as originally developed by May.[20] During the initial determination, it was concluded that the droplets being produced were generally too coarse for good projection of the spray. Many large droplets were formed which were projected only a relatively short distance prior to settling out of the spray. As illustrated from the experimental data shown in Figure 7, a number mean droplet size of ~ 80 μm was measured for the spray originally produced by the fogger.
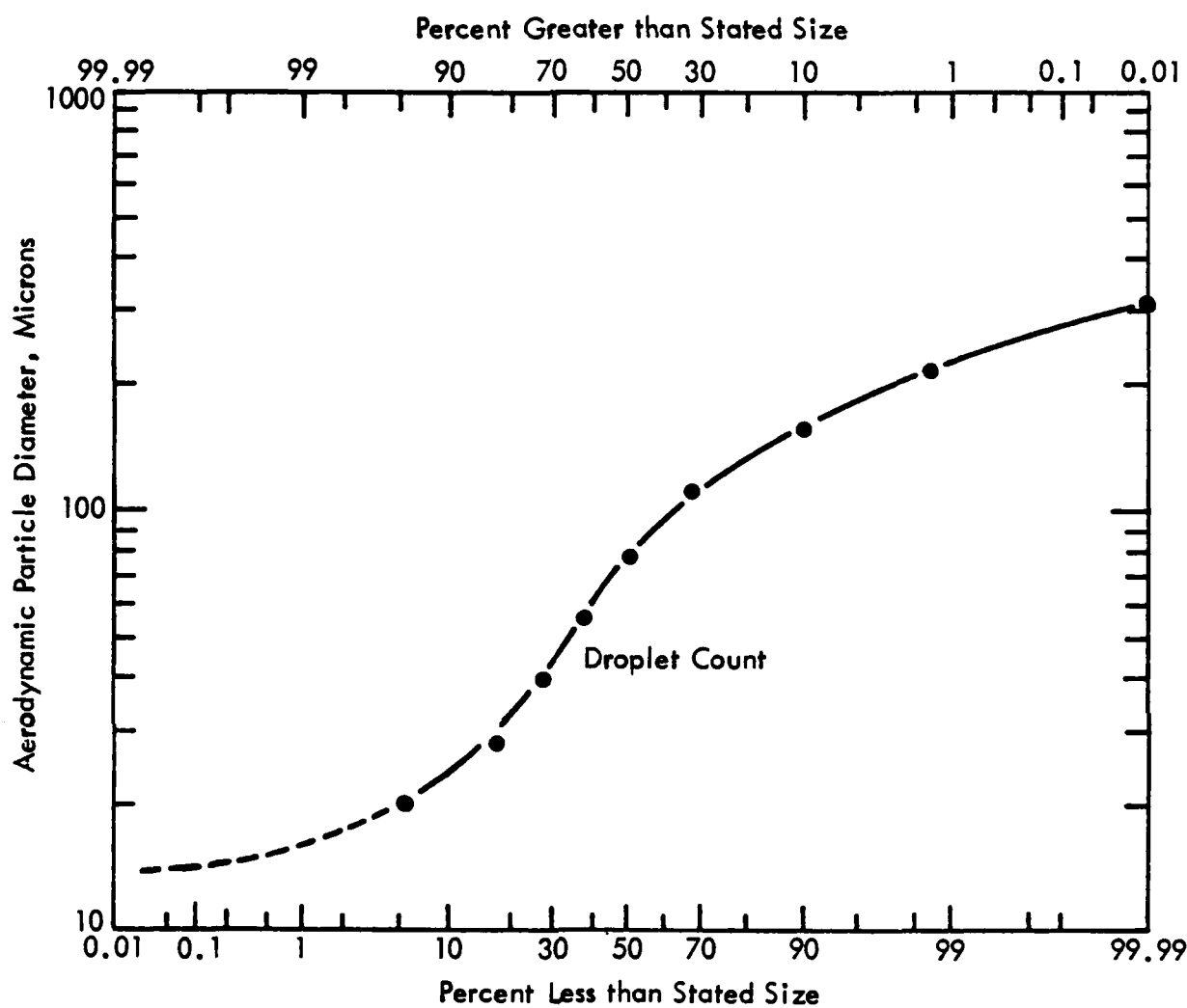
17

Figure 7. Original number distribution of droplets generated by electrostatic fogger.

To correct the above problem, certain internal modifications were made to the atomizing cup using the work of Fraser, Dombrowski, and Routley in the United Kingdom.[21-23] These modifications mainly involved the installation of a weir to produce a more even film of water flowing toward the lip of the atomizing cup. The cup modifications not only made a significant improvement in the overall spray pattern but also significantly decreased the size of the droplets.

Figure 8 provides droplet size data for the spray produced by the fogger after modifications to the atomizing cup were implemented. As can be seen from these data, the number mean droplet size is around 47 μm with a significantly greater number of small droplets present. This droplet spectrum was considered to be appropriate for testing in the experimental chamber.

In conclusion, the fogger developed is generally better suited for use in firefighting because of its lighter weight and improved operating characteristics. The most effective of previous devices have weighed in excess of 45 kg (100 lb) as compared to the present design's 18 kg (40 lb). This fogger is also considerably more effective in imparting an electrostatic charge onto the droplets. As indicated in Section 4.0, the charge-to-mass ratio of the droplets is approximately six times greater than for earlier foggers of a similar capacity which produce droplets of comparable size. Equations (1) and (2) would indicate, therefore, that the present design's efficiency should be considerably higher because of this greater level of charge on the droplets.
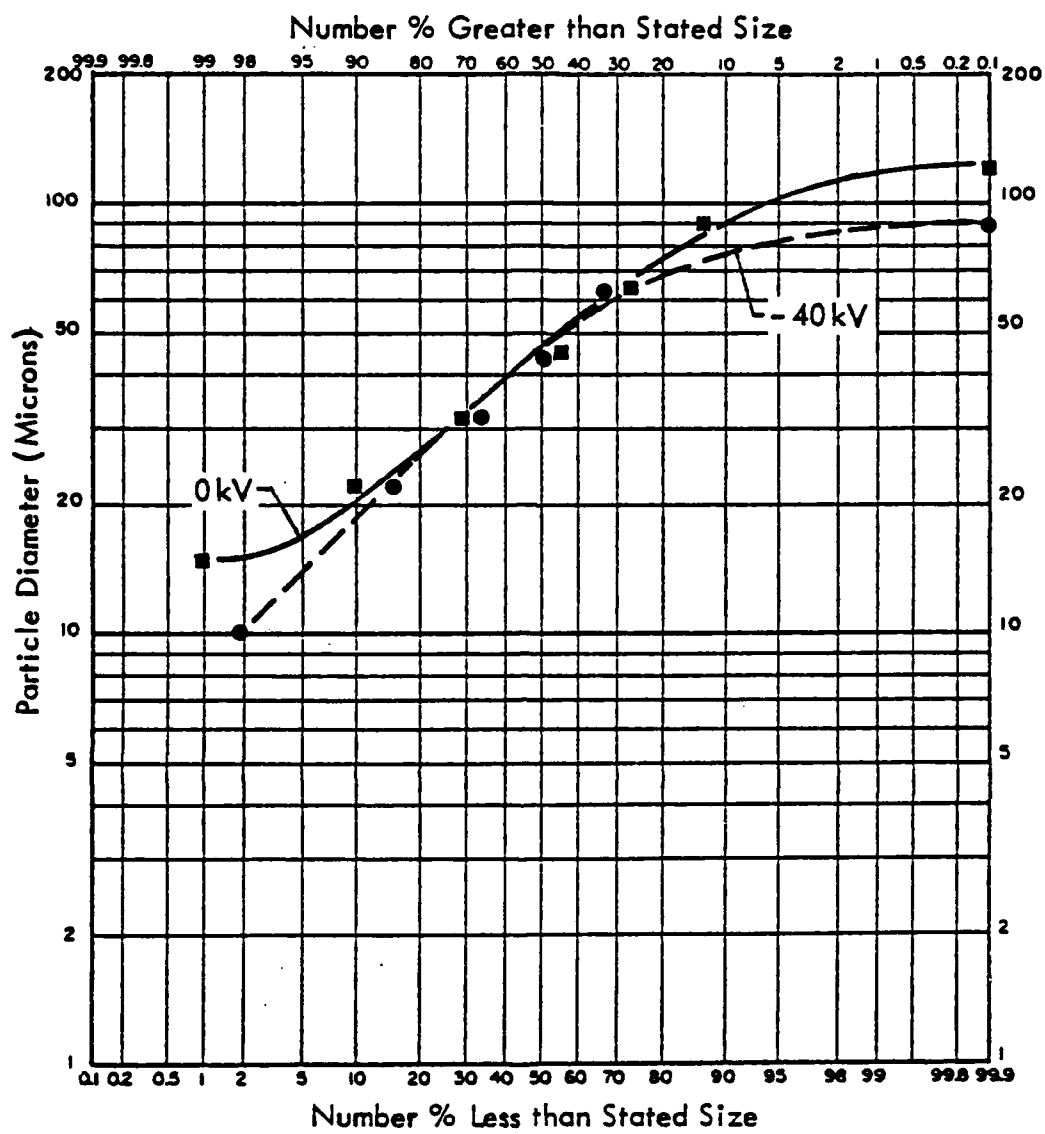
Figure 8.   Number distribution of droplets generated by
modified electrostatic fogger.

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4. EXPERIMENTAL PROGRAM

As stated previously, the smoke clearing capabilities of the fogger described in Section 3 was evaluated under controlled laboratory conditions. The following section describes the apparatus, procedures, and data collected during the experimental effort.

4.1 EXPERIMENTAL APPARATUS

In order to test the fogger's smoke clearing ability under controlled conditions, a test chamber and associated instrumentation was assembled for use in the program. A standard 4.5-m³ inhalation chamber was modified for these experiments. Modifications or additions made to the chamber included: reversal of the airflow through the chamber; fabrication and installation of an aerosol (smoke) generator; installation of an He-Ne laser transmissometer (and associated electronics); and installation of appropriate instrumentation for monitoring the size and concentration of the aerosol in the chamber. A diagram of the chamber and related instrumentation is shown in Figure 9.

The test chamber modified for use in the program was a standard Rochester inhalation chamber traditionally used by MRI for animal research studies. To provide the appropriate airflow configuration through the chamber, the ductwork was reversed such that the air moved in an upward direction countercurrent to the spray generated by the fogger (Figure 9). These modifications also allowed both the aerosol (smoke) to be vented through a thermal oxidizer (afterburner) located on the roof of the building as well as providing for the installation of the aerosol (smoke) generator described below. Ventilation through the chamber could be controlled as required for experimentation purposes. The airflow rate into the chamber was measured by a calibrated orifice meter installed upstream of the smoke generator in the inlet ductwork.
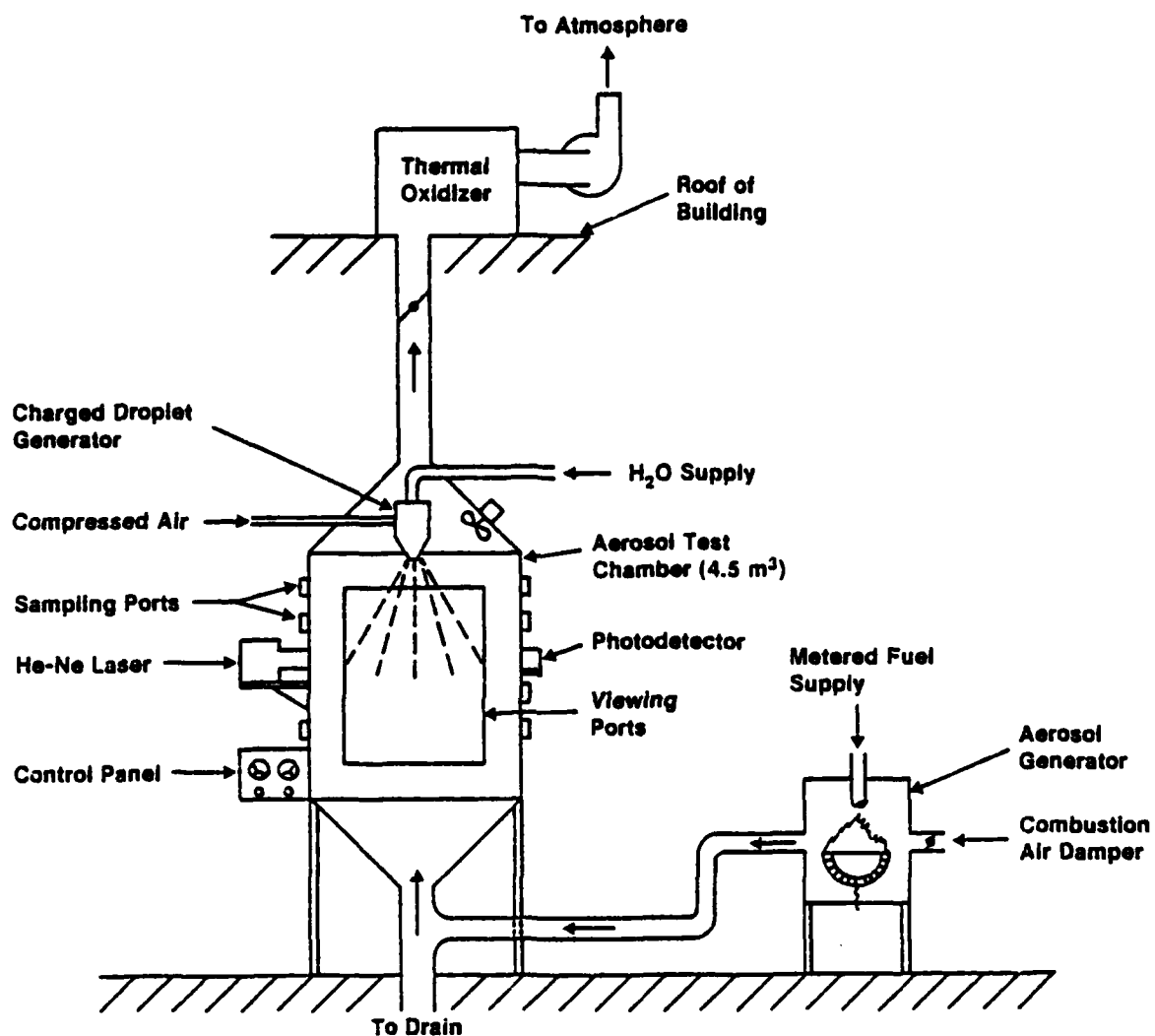
21

Figure 9. Diagram of aerosol chamber and associated instrumentation.

Smoke was introduced into the test chamber from an aerosol generator installed in the inlet ductwork system. The test aerosol (smoke) was produced in the generator by the incomplete combustion (and pyrolysis) of No. 2 fuel oil by dripping fuel into a stainless steel reservoir. A natural gas pilot was provided in the smoke generator for ignition of the fuel. Fuel oil was metered to the generator through a control valve installed in the supply line feeding the unit.

To measure the total light transmission through the aerosol (smoke) on a quantitative basis, a laser transmissometer was installed in the test chamber. A 0.8-mW He-Ne laser (wavelength ~ 0.63 m) and photoelectric detector was used in the transmissometer to continuously monitor the transmission of light across the width of the chamber. The output from the photodetector was connected to a strip chart recorder for continuous data logging. The beam path of the laser was located above the spray produced by the fogger to reduce the contribution of the water droplets to the overall reduction in light transmission. Mixing fans were operated during testing to provide a well stirred aerosol cloud throughout the chamber volume. Floodlights were also installed on the outside of the rear viewing port of the chamber for visual observation of the smoke clearing process.

In conjunction with monitoring the light transmission across the chamber, both the concentration (number of particles per cubic meter) and size (physical diameter or μmP) distribution of the particles making up the test aerosol were also determined on a continuous basis. The measurement system used in this regard consisted of: a sampling probe; K^{85} charge neutralizer; porous tube dilution apparatus; and a Climet Model 208A optical particle counter (OPC) and associated Model 209 printer/counter. A General Electric condensation nuclei counter (CNC) was also available for use in the study but was determined to be less applicable to the experiments conducted. The Climet instrument was completely realigned and recalibrated prior to use in the study. The aerosol monitoring system used in conjunction with the test chamber is illustrated in Figure 10.

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AIR DILUTION SYSTEM

Sampling Probe

Chamber Wall

K^{85} Charge Neutralizer

Porous Metal Screen

To Optical Particle Counter

Series 100 Flow Transducer

Blower

To Exhaust

Absolute Filter

Inclined Manometer
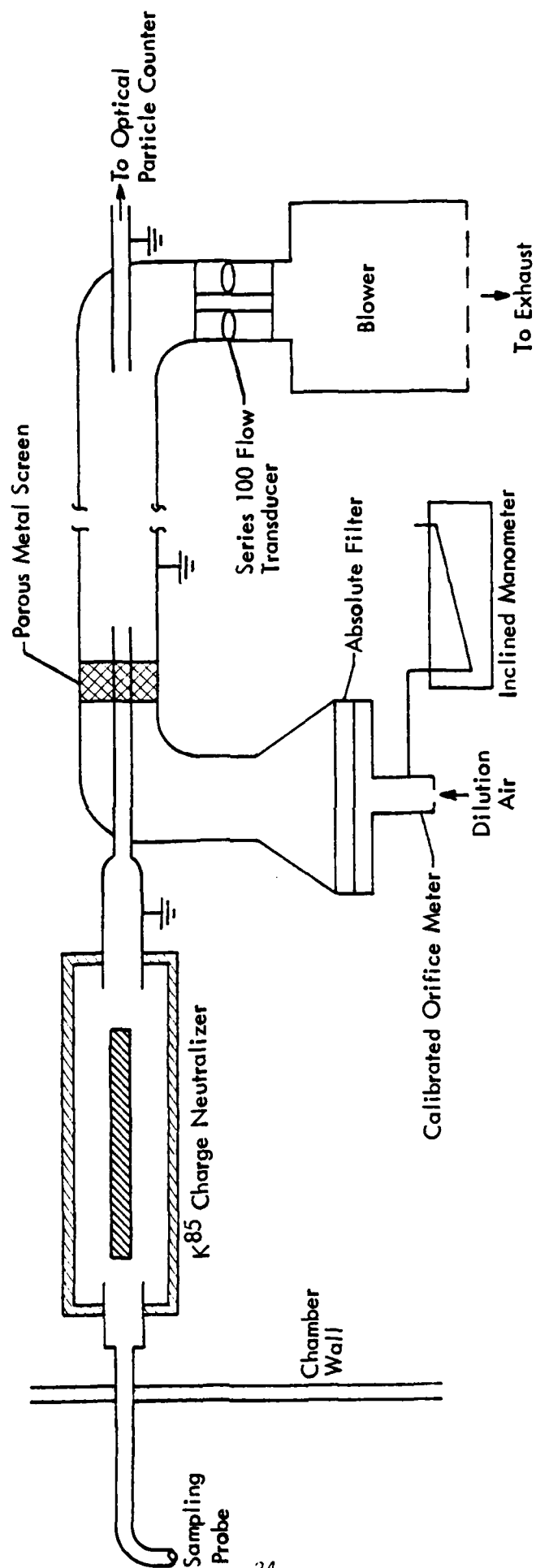
Dilution Air

Calibrated Orifice Meter

Figure 10. Diagram of aerosol sampling equipment.

For characterization of the aerosol during each test, a sample of gas was continuously extracted from the chamber at a constant flow rate ($\sim$ 12 L/min). A copper sampling probe was used for sample extraction. Isokinetic sampling was not attempted (or needed) since, in most cases, there was no airflow through the chamber and the particles were generally of a size (e.g., predominately 0.3 to 0.5 μm in physical diameter) that inertial effects were not considered to be significant for representative sampling.

As stated in Section 2 above, most aerosol particles become electrically charged during generation. To reduce unwanted electrostatic effects associated with the suspended particles in the measurement system, the aerosol was passed through a K^{85} charge neutralizer. The low level, radioactive source in the neutralizer produces a cloud of small, bipolar ions which discharge the particles in the system to obtain a Boltzmann's equilibrium charge distribution on the suspended particles.[24] In addition, to further reduce the electrostatic interaction between the suspended particles and the walls of the sampling system, the entire apparatus was electrically grounded, as was the test chamber itself.

To substantially reduce potential measurement errors in the OPC due to coincidence loss in the sensing volume, a porous tube dilution apparatus was also fabricated using the concepts developed by Fenton, Ranade, and other investigators.[25,26] This apparatus was used to significantly reduce the concentration of the particles in the aerosol being analyzed.

In the dilution apparatus, a flow of filtered air is mixed with the sample flow to provide a dilute aerosol suitable for analysis by the OPC. All flow measuring devices used in the dilution system were calibrated against a primary reference standard (Roots meter). During all experiments conducted, the original aerosol from the chamber was diluted by a factor of $\sim$ 42 from its initial concentration. According to manufacturer's data, the maximum coincidence loss which might be expected for the actual particle concentrations measured would be 1.13%. This degree of experimental error was deemed acceptable for the purpose of this particular study.

Finally, the charge-to-mass ratio (C/M) of the water droplets was determined using a Faraday cup apparatus developed by the principal investigator on a previous study.[9] This apparatus consisted of an insulated stainless steel probe mounted on a standard glass impinger. The probe was electrically connected to steel wool packing and copper foil placed inside the impinger which was subsequently connected by a shielded cable to a Keithly electrometer (and associated strip chart recorder). The impinger was immersed in a Dewar flask containing dry ice. A silica gel drying tube was installed downstream of the impinger to trap any water which escaped collection in the impinger.

During testing, a sample of the water droplets produced by the fogger was extracted from the spray by the sampling train. As the droplets moved through the impinger, they were separated out of the gas stream and subsequently frozen. During this process, the charge on the droplets was transferred to either the steel wool packing, probe, or copper foil. By grounding the entire system through the electrometer, the charge on the droplets were measured and subsequently recorded by the chart recorder. The mass of water collected in the impinger and silica gel trap was determined gravimetrically at the end of each test using a triple-beam balance. Proper sampling conditions were maintained through the train by a calibrated flowmeter and needle valve with a diaphragm pump acting as prime mover. The volume of gas sampled was determined by means of a calibrated dry gas meter. An illustration of the charge-to-mass apparatus used in the study is shown in Figure 11.

4.2 EXPERIMENTAL PROCEDURES

The following procedures were used to conduct the various experiments performed in the study.

4.2.1 Smoke Clearing Experiments

The same basic procedure was followed during all smoke clearing tests, regardless of the particular experiment being conducted. First, all of the
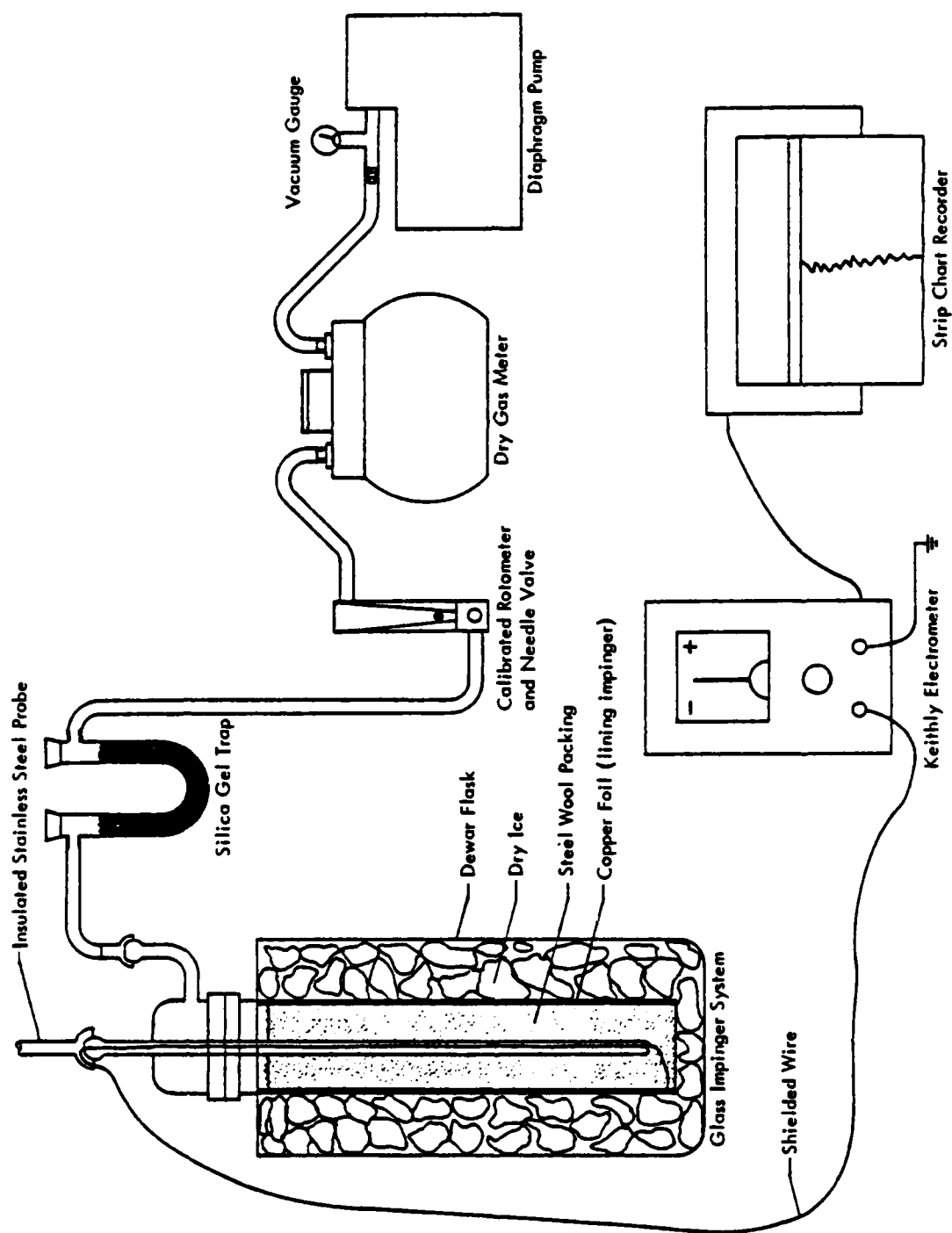
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Figure 11. Diagram of charge-to-mass apparatus.

various instruments were activated and initially checked for proper operation. In the case of the laser transmissometer, the instrument was optically aligned as well as being zeroed and spanned at 0 and 100% transmission, respectively. The zero and span values were then recorded on the strip chart along with the date, time, chart speed, and other important parameters for future reference.

For the Climet OPC, the instrument was initially operated for a minimum of 30 min prior to testing per manufacturer's specifications. After completion of the requisite warm-up period, the OPC was then taken through its internal (optical) calibration procedure and minor adjustments made, as necessary. Upon completion of the internal calibration, the instrument was set for continuous operation with data collected at specific time intervals (usually 1 min).

Also during the initial warm-up period, the air dilution system was turned on and the various flows set to preselected values based on expected particle concentrations. The flowmeter of the OPC was set to the recommended 2.54 cm (1.0 in.) of H_2O which corresponded to a flow through the instrument of 7.1 L/min or 0.25 ft^3/min. The sample flow from the chamber was adjusted to 12 L/min (0.43 ft^3/min) for each test with 499.0 L/min (17.62 ft^3/min) of filtered dilution air being provided by the system. These flow rates resulted in a dilution factor of 42 for all tests conducted. This value was used to correct the particle concentrations measured by the OPC to that which actually existed in the test chamber.

After checking and calibrating all measurement equipment, smoke was introduced into the chamber by feeding fuel to the aerosol generator at a constant rate. Smoke was introduced until such time that both the laser transmissometer indicated 0% light transmission (or an appropriate minimum value) and the floodlights located at the rear of the chamber could no longer be observed visually. At this point, the fuel flow was shut off and either the fogger was activated to clear the smoke in the chamber or the smoke was allowed to dissipate by natural processes. No tests were conducted involving the continuous generation of smoke into the chamber.

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During each test, data were collected on a continuous basis with appropriate notations made on the strip chart, the OPC printout, a bound laboratory notebook, or all three. Experiments were conducted with no fog and with charged fog at various applied potentials. In addition, transmissometer measurements were also made with a small airflow (0.45 m³/min) through the test chamber for comparison purposes. Tests with fog but no applied potential were attempted but were determined not to be representative, thus the data have not been reported. Limitations in available resources precluded any further attempts to collect these particular data.

4.2.2 Charge-to-Mass Measurements

For each C/M test, the impinger and silica gel trap were initially weighed on the triple beam balance and the weights recorded and transferred to the lab notebook. The apparatus was then reassembled and dry ice added to the Dewar. The impinger/trap system was then placed in the test chamber, the fogger activated, and the probe unsealed. The spray was then sampled for a period of 7 to 10 min after which time the probe was resealed, the airflow through the sampling train shut off, and the fogger deactivated.

Upon completion of the test, the impinger and silica gel trap were removed from the sampling train, wiped completely dry with a cloth, and reweighed on the triple beam balance. By graphically integrating the area under the curve generated by the strip chart recorder (using a planimeter), the total charge on the water droplets collected in the sampling train was obtained. All pertinent test parameters, including tare and sample weights, were noted on the strip chart recordings, the laboratory notebook, or both. Tests of the C/M of the water droplets generated by the fogger were conducted for fog with no applied potential as well as for applied potentials of -20, -40, and -60 kV, respectively.

4.3 EXPERIMENTAL RESULTS

4.3.1 Smoke Clearing Tests

The experimental data obtained during the smoke clearing tests conducted during the program are presented in Tables 1 and 2. Table 1 provides light transmission data obtained from the laser transmissometer; Table 2 shows the experimental data collected by the Climet instrument and associated air dilution system.

TABLE 1. Percent Light Transmission for Various
Fogger Operating Conditions.[a]

| Flow through chamber[b] | Test scenario | Time to reach stated light transmission (min)[d] | | |
		25% transmission	50% transmission	100% transmission
No flow	No fog	17.5	21.0	110.0
	Fog: -40 kV	4.0	7.0	27.0
	Fog: -60 kV	3.4	6.4	17.4
0.45 m³/min	No fog	3.3	5.7	14.6
	Fog: -20 kV	2.4	4.2	~ 9
	Fog: -40 kV	1.5	3.0	~ 8

[a] Light transmission as determined by a 0.8-mW He-Ne laser transmissometer as recorded by a strip chart recorder. Smoke was determined to be visually cleared within 15 to 60 sec after activation of the fogger.

[b] Flow rate through the test chamber as measured by a calibrated orifice meter.

[c] Voltages indicated are the potentials applied to the fogger during testing.

[d] Period of time required to reach either 25, 50, or 100% light transmission as measured by the transmissometer.

Unfortunately, only one test could be conducted for each experimental scenario. More appropriately, at least duplicate, if not triplicate, tests are needed to increase the reliability of the data collected. However, such was not possible in this study given available funding levels.

Table 2. Particle Concentrations Measured by Climet OPC During Smoke Clearing Experiments

Experimental scenario[a]	Time increment (min)	Particle number concentration measured in each size range (10^3 particles/m^3)[b]						Total particle count
		0.3-0.5 μm	0.5-1.0 μm	1.0-3.0 μm	3.0-5.0 μm	5.0-10.0 μm	> 10 μm	
Smoke only	1	535.1	409.0	297.9	220.5	105.6	53.0	1,621.0
	3	267.5	267.4	270.6	294.9	288.2	387.1	1,776.1
	4	212.2	218.4	228.0	256.8	287.7	491.0	1,694.1
	5	123.6	202.2	210.0	221.8	221.8	529.1	1,703.0
	6	197.1	203.6	215.9	247.2	295.8	568.5	1,728.0
	7	248.8	250.7	259.8	294.3	310.7	473.9	1,838.2
	8	387.5	360.2	342.8	352.5	266.1	185.2	1,894.2
	9	478.6	408.8	352.1	313.2	169.5	65.3	1,787.5
	11	641.3	414.6	248.9	133.4	32.1	6.6	1,601.3
	21	487.8	80.0	12.7	2.1	0.2	0.1	583.0
	26	322.8	29.7	3.46	0.56	Nil	Nil	356.65
	31	181.7	10.5	1.1	0.18	Nil	Nil	193.52
	41	57.99	1.79	0.18	Nil	Nil	Nil	60.04
	46	32.17	0.84	0.1	Nil	Nil	Nil	33.18
	51	18.03	13.51	5.93	0.1	Nil	Nil	18.50
	61	5.93	0.1	Nil	Nil	Nil	Nil	6.06
	66	3.71	Nil	Nil	Nil	Nil	Nil	3.77
	71	2.39	Nil	Nil	Nil	Nil	Nil	2.45
	81	1.1	Nil	Nil	Nil	Nil	Nil	1.23
Fogger (-40 kV)	1	333.6	318.3	324.5	358.1	351.2	436.3	2,121.9
	2	433.5	384.4	362.5	370.1	282.3	208.1	2,040.9
	3	520.6	420.5	361.5	324.4	191.5	97.7	1,916.3
	4	579.4	430.2	333.8	266.3	128.2	53.4	1,791.3
	5	620.5	421.7	297.3	211.3	87.1	32.0	1,669.9
	7	644.3	395.6	252.4	159.6	57.2	19.2	1,528.2
	8	654.6	364.1	209.9	120.9	39.3	12.3	1,401.1
	9	650.9	328.8	172.8	91.5	26.9	8.6	1,279.5
	11	615.6	247.3	110.3	49.4	13.2	4.1	1,040
	12	580.8	213.0	87.5	37.8	9.6	2.9	931.7
	13	542.9	181.7	70.2	30.1	7.5	2.1	834.6
	14	496.2	149.9	54.7	22.0	5.2	1.7	729.8
	15	443.6	120.7	41.9	16.3	3.8	1	627.4
	17	389.5	97.5	31.8	12.0	2.7	1	534.4
	18	343.1	79.4	25.1	9.3	2.0	0.7	458.9

TABLE 2.Continued

| Experimental scenario[a] | Time increment (min) | Particle number concentration measured in each size range (10^3 particles/m^3)[b] | | | | | | Total particle count |
		0.3-0.5 μm	0.5-1.0 μm	1.0-3.0 μm	3.0-5.0 μm	5.0-10.0 μm	> 10 μm	
Fogger (-40 kV) (continued)	19	298.2	64.3	19.9	7.0	1.5	0.6	391.5
	20	256.9	51.5	15.2	5.4	1	0.4	330.5
	21	220.0	41.9	12.1	4.0	1	0.4	279.4
	22	188.6	34.4	0.96	0.35	0.6	0.2	236.9
	23	161.6	28.3	7.5	2.5	0.5	0.1	200.5
	24	139.0	23.2	6.3	2.1	0.6	0.1	171.1
	25	119.1	18.9	5.0	1.7	0.4	0.1	145.2
	27	100.8	15.7	4.0	1.2	0.2	Nil	122.0
Fogger (-60 kv)	1	301.3	298.8	312.9	349.3	351.1	461.4	2,074.6
	2	413.2	386.8	372.5	380.6	291.4	207.7	2,052.2
	4	519.6	446.8	387.7	340.7	183.9	68.2	1,946.8
	5	612.4	473.7	357.4	252.4	90.9	20.3	1,807.1
	6	685.8	464.9	296.4	165.9	41.7	7.0	1,661.7
	7	730.2	429.7	226.8	100.9	18.8	3.1	1,509.5
	8	757.9	382.1	169.7	60.6	0.88	1.6	1,380.6
	9	754.2	324.0	120.1	35.6	4.5	1	1,239.4
	10	737.9	266.0	83.7	21.3	2.4	0.6	1,112
	11	704.6	219.2	60.5	13.3	1.5	0.4	999.5
	13	666.4	178.1	43.3	8.7	1	0.2	897.7
	14	636.3	157.0	36.1	7.0	0.7	0.2	837.3
	15	654.3	241.7	95.4	35.7	6.0	0.7	1,034
	16	537.9	112	24.8	4.9	0.6	0.1	680.1
	17	448.0	66.8	11	2.0	0.2	0.1	528.4
	18	359.6	42.6	6.4	1.2	0.1	0.1	410.1
	19	288.7	29.4	4.3	0.8	0.1	Nil	323.3
	20	234.9	20.7	3.1	0.7	0.1	Nil	259.5

[a] Voltages indicated are the potentials applied to the fogger during each test.
[b] Actual concentration of particles in the test chamber after taking into account the amount of dilution air provided in the measurement system. Values rounded to the same number of significant figures as original data. Particle size = μm physical diameter.

Visually, it was determined during all tests conducted that smoke could be successfully cleared from the chamber within a period of 15 to 60 sec after application of charged fog. However, as shown in Table 1, as much as 27 min were required to completely clear the chamber as determined by the laser transmissometer system (with no airflow through the chamber). This would be expected, however, since only a relatively small concentration of absorbing particles (i.e., smoke), would be required to significantly attenuate the electromagnetic radiation produced by the laser. Thus, a longer time period would be required for the transmission measured by the laser transmissometer to reach 100%.

Also shown in Table 1 is the fact that charged fog does significantly reduce the time required to reach a given level of transmission. In addition, the time required also decreases with increasing potential applied to the fogger. It can be seen, therefore, that charged fog does substantially enhance smoke clearing beyond that which occurs by natural removal processes.

With regard to the concentration of smoke in the chamber, the data in Table 2 also provide some interesting results. These results are illustrated in Figures 12 to 14 which are graphs of concentration data obtained from the OPC for various particle size fractions and experimental scenarios. In the case of the total particle concentration (Figure 12), it can be seen that the concentration in the chamber drops off significantly faster upon application of the charged fog than is the case for natural removal processes (i.e., smoke only). A similar observation can also be made for the larger (i.e., > 10 μmP) particles contained in the aerosol, as shown in Figure 13.

With regard to submicron (i.e., 0.3 to 0.5 μmP) particulate, the data in Figure 14 would suggest that operation of the fogger initially produces additional fine particles (over and above the smoke itself) with the concentration decreasing more rapidly at later time periods. This could be partially explained by the fact that water entering the dilution system in the vapor state may have been recondensed upon cooling thus producing additional fine particles which were subsequently measured by the OPC. If this was the case, the problem could have been alleviated by the addition of a diffusion dryer to the air dilution system. However, available resources precluded any further fabrication of equipment.
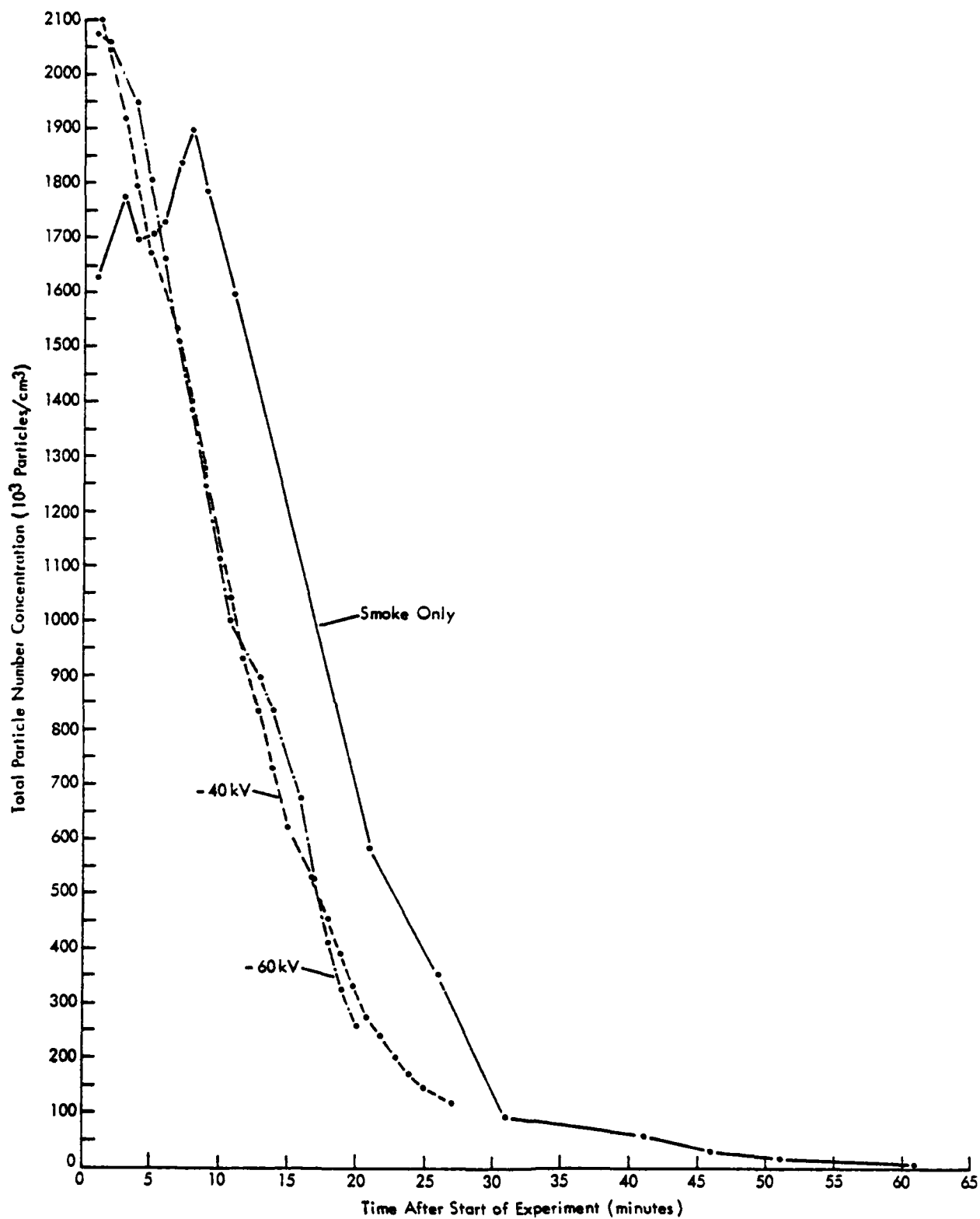
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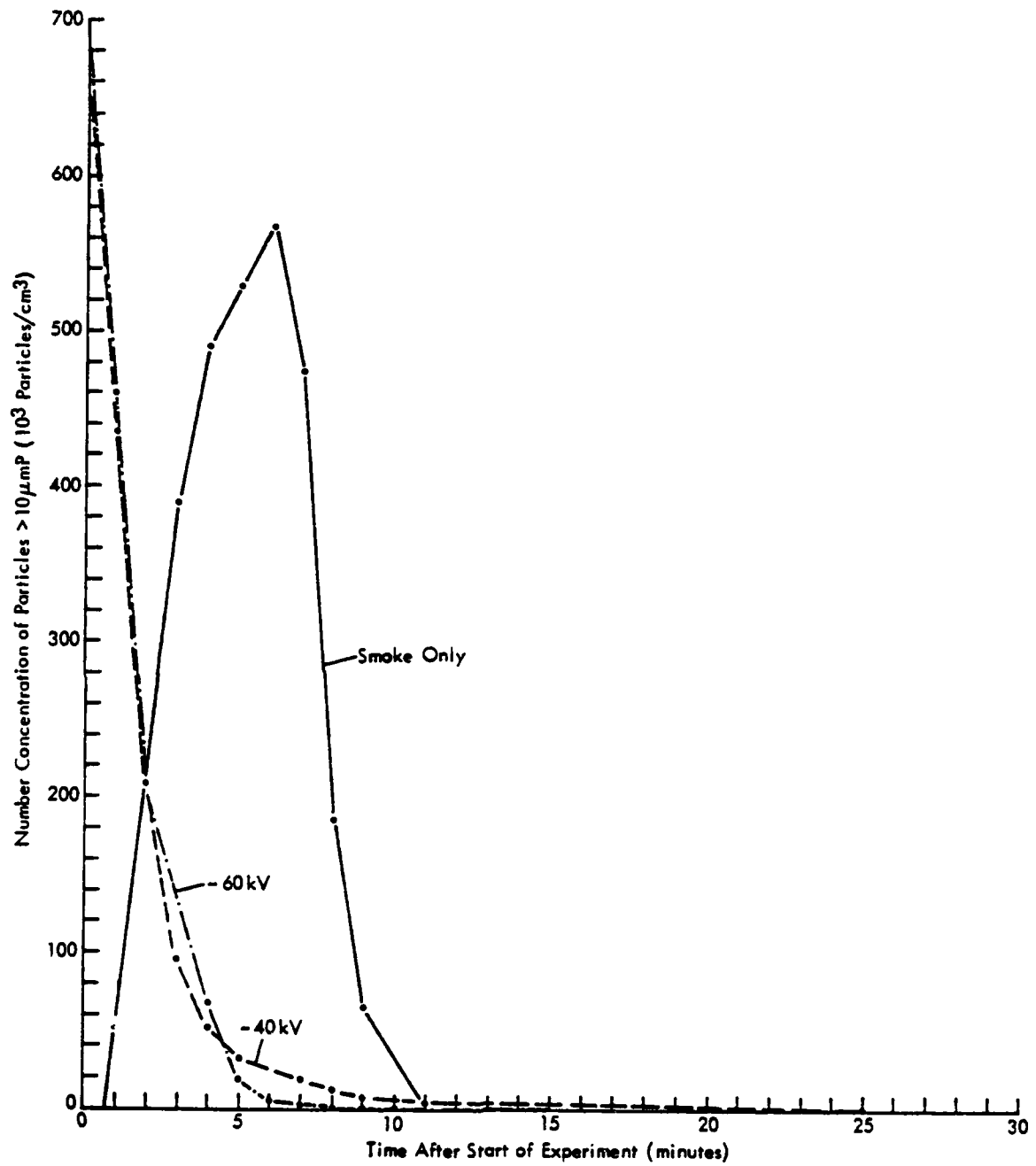Figure 12. Total particle concentration versus time as determined by the Climet OPC.

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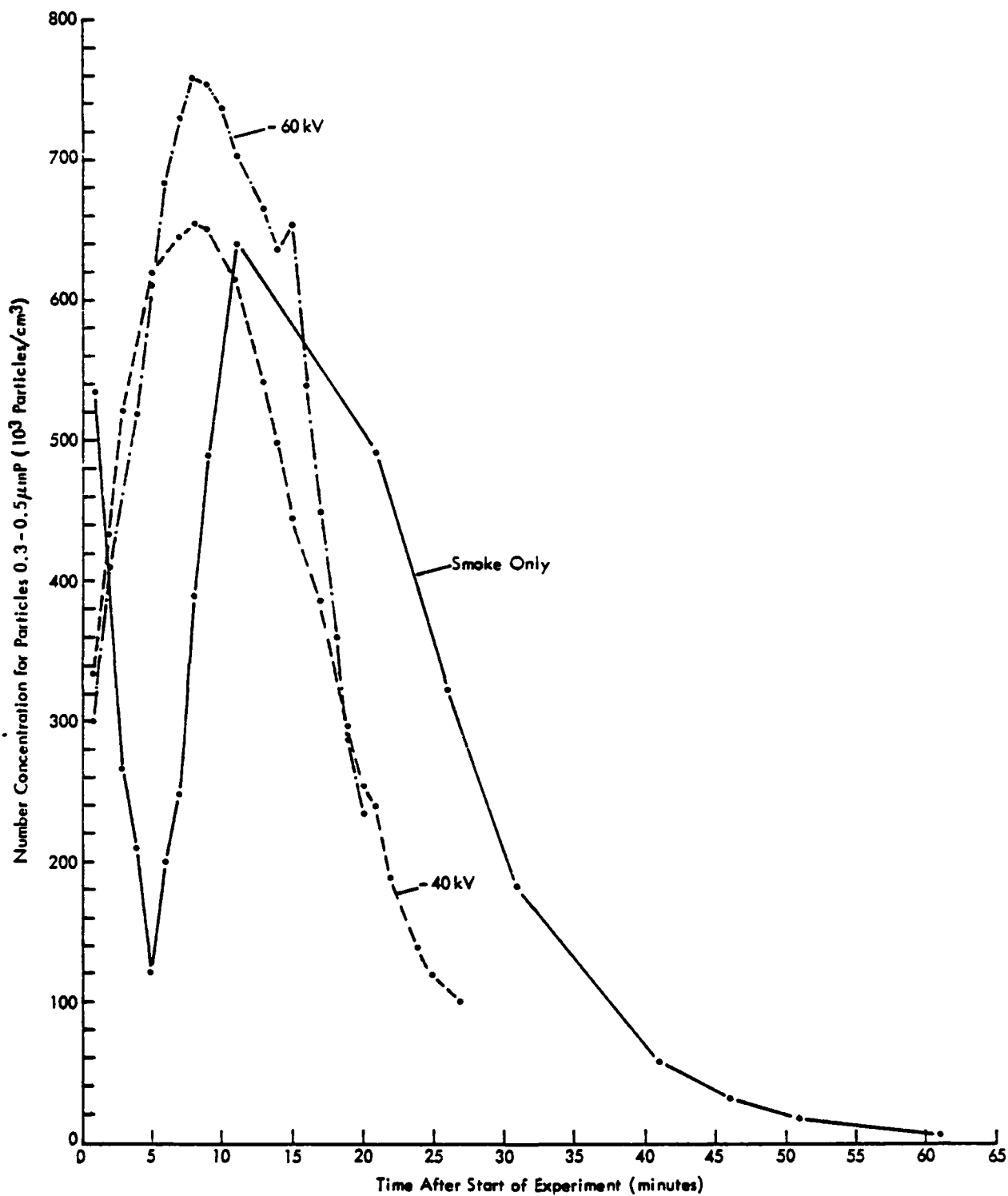Figure 13. Number concentration of particles > 10 μmP versus time as measured by the Climet OPC.

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Figure 14. Number concentration of particles 0.3-0.5 µmP versus time as measured by the Climet OPC.

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4.3.2 Charge-to-Mass Measurements

The results of the C/M measurements conducted in the study are shown in Table 3 for various applied potentials. As shown, extremely high C/M values were determined for the water droplets generated by the fogger with a maximum of ~ $68(10)^{-6}$ C/g being obtained at an applied potential of -60 kV.

TABLE 3. Results of Charge-to-Mass Measurements.

Applied potential (kV)	Water flow rate to fogger (L/min)	Total charge measured (10^{-6} Coulombs)	Mass of water collected (g)	Charge/mass ratio (10^{-6} C/g)
0	0.95	7.5	3.4	2.2
-20	0.95	35.8	3.3	10.9
-40	0.95	227	5.7	39.8
-60	0.95	182	2.7	67.5

Another factor which should be noted with regard to the data contained in Table 3 is the fact that the water droplets produced by the fogger without an applied potential are not completely uncharged. Generally, the spray tends to be slightly negatively charged. This result is not unexpected based on data collected by other investigators which indicate the production of similar negatively charged droplets due to the phenomena of "spray electrification."[27] A value of $6(10)^{-10}$ C/g has been reported for pure water with the addition of certain dissolved salts (as is the case here) tending to increase the level of charge on the droplets.[27] Therefore, all atomizers, regardless of design, will generate charged droplets to a limited extent but at relatively low charge levels.

Finally, to illustrate how the C/M values obtained in the present study compare with similar devices, Table 4 presents published data for four other electrostatically augmented atomizers.[10,19,28,29] As shown in Table 4, the C/M of the droplets produced by the current fogger either meet or exceed that generated by the other devices listed at comparable applied

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TABLE 4. Typical Charge-to-Mass Ratios for Electrostatically Augmented Atomizers

Type of atomizer	Type of charging mechanism	Liquid output rate (cm³/min)	Applied voltage (kV)	C/M ratio (10⁻⁶ C/g)	Reference[a]
Two-fluid[b]	Induction	80	2	4.8	Law, 1978
Electrodynamic[c]	Contact	12	20	10	Coffee, 1980
Two-fluid[d]	Induction	38(10)³	12.5	0.1	Brookman, 1983
Rotary[e]	Contact	950	15	1.2	Mathai, 1983
Rotary	Contact	950	20	10.9	Present study

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a See references listed in Section 6 of this report.
b "Embedded - Electrode Electrostatic - Induction Spray - Charging Nozzle" used for pesticide/herbicide application.
c "Electrodyn" used for pesticide/herbicide application. This device uses electrostatic (not mechanical or shear) forces to accomplish droplet breakup.
d Ritten Corporation "Fogger IV."
e AeroVironment "Charged Fog Generator."

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voltages. In addition, the MRI device is also capable of a C/M which is far in excess of that achieved by the other equipment. Therefore, such data would indicate that the fogger developed in this particular study is, in many respects, superior to similar devices of a comparable capacity and thus represents a significant step forward in the development of charged fog technology.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

There are a number of conclusions which can be reached from the data obtained in the study. First, it was determined from visual observations that smoke can be effectively cleared from a 4.5-m³ test chamber within 15 to 60 sec after application of charged fog. Moreover, the data collected by the laser transmissometer would also indicate that charged fog significantly decreases the time required to reach a given level of transmission as compared to natural removal processes. This trend is further substantiated by the data obtained from the Climet OPC.

The second conclusion reached is the fact that the novel device designed and developed for this study is superior in many respects to similar equipment developed by other investigators. This conclusion is based on a comparison of certain key operational parameters (e.g., C/M) considered to be important in the removal of suspended particles by electrostatic forces. Therefore, a significant advancement has been made in the development of charged fog technology.

Finally, additional measurements would be required to substantiate the experimental data collected during the study. At least duplicate, if not triplicate, tests should be conducted for each operational scenario to increase the reliability of the information obtained.

5.2 RECOMMENDATIONS

The charged droplet generator (electrostatic fogger) developed by MRI in the study weighs approximately 18 kg (40 lb) and requires significant external support (i.e., water, compressed air, and electric power). The present unit operates efficiently under experimental conditions, but is not practical for use in harsh environments (e.g., shipboard fires). Thus, for actual firefighting purposes, an improved version of electrostatic fogger is needed which is both compact and as self-contained as possible. Once a

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suitable device has been developed, representative field trials can then be conducted to evaluate the true efficacy of charged fog to clear smoke in an actual shipboard fire.

Therefore, as the next logical step, it is recommended that an improved version of electrostatic fogger be developed which is suitable for testing in the field. This fogger should incorporate a number of design improvements over the current unit as well as provide its own source of electric power, if possible. Further work is necessary, therefore, to provide a truly practical system for use under representative firefighting conditions. The present unit does, however, substantiate the fact that the use of charged fog is a viable concept for smoke clearing and should be pursued vigorously in the future.

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